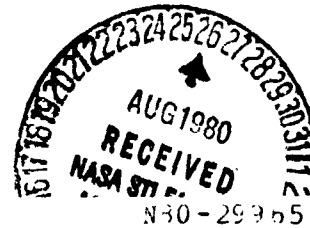


**NASA CONTRACTOR
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NASA CR-161490

(NASA-CR-161490) CLOUD COVER MODELS DERIVED
FROM SATELLITE RADIATION MEASUREMENTS Final
Report (University of Central Florida) 38 p
HC A03/M1 A01 CSCL 04B



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**CLOUD COVER MODELS DERIVED FROM SATELLITE RADIATION
MEASUREMENTS**

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Final Report

November 14, 1979

Prepared for

**NASA - George C. Marshall Space Flight Center
Marshall Space Flight Center, Alabama 35812**

ACKNOWLEDGEMENTS

The authors are indebted to O.E. Smith, Marshall Space Flight Center, for introducing the problem, and for many helpful discussions and comments.

The efforts of Roy Jenne and his coworkers at NCAR in furnishing the data sets for this study are gratefully acknowledged.

The assistance of Chris Maukenon in developing many of the computer programs used in the investigation was invaluable.

The conscientious and painstaking efforts of Sarah Autrey and Debbie Waitt in many elements of the project and especially their efforts in developing the graphics have resulted in significant contributions and are greatly appreciated.

The authors are grateful to Cindy Sloan for her careful and conscientious efforts in typing the report.

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INTRODUCTION

The purpose of this study was to develop a model for worldwide cloud cover using a satellite data set containing infrared radiation measurements. Other cloud models exist [1-3]. These early cloud models used primarily ground-based cloud observations. The satellite data set containing Day IR, Night IR, Incoming, and Absorbed solar radiation measurements on a 2.5-degree latitude-longitude grid covering a 45 month period of record has recently become available. There was originally a 2-year period of similar data on an NMC grid. The first step was to convert these infrared data to estimates of cloud cover. The statistical analysis of classification of cloud region characteristics was then performed.

There are several reasons for desiring a cloud model based on satellite data. The ground-based data are much more limited in scope. Some fairly large areas of the world have either no data or very sparse data, and models using ground-based observations necessitate a number of assumptions, including on occasion that a region is essentially like its antipodal location. A good worldwide cloud cover model is needed for the purpose of studying the relationship between cloudiness, precipitation, and the Earth radiation budget.

CONVERSION OF SATELLITE IR MEASUREMENTS TO CLOUD COVER

A major initial task was to derive cloud cover estimates from the satellite infrared data. The method used in this investigation follows the suggestions obtained through personal communications with Thomas I. Gray, Jr. [4].

Albedo is defined as the reflective power, or the fraction of incident light that is reflected by a surface or body. Included in

the satellite data are the amount of incoming solar radiation, I_{in} , and the amount of absorbed solar radiation, I_{ab} . The satellite observed albedo A , is estimated by

$$A = (I_{in} - I_{ab})/I_{in} \quad (1)$$

If the Earth's surface absorbed all solar radiation, then the cloud cover might be taken simply as 1 minus albedo (assuming also that clouds reflect all solar radiation). Different parts of the Earth's surface, however, have differing radiances. For example, the albedo of the ocean is approximately 5 percent (95 percent of the solar radiation being absorbed), while the Sahara desert reflects approximately 40 percent of the solar radiation reaching it.

To determine cloud cover, we needed to obtain the background radiation of the region of the Earth of interest. To do this, for a given season and a specified location, we calculated A from equation (1) for every day of a season and observed the minimum value, A_{min} . This minimum value should occur on the day of least (hopefully near zero) cloud cover. If r is the reflectance of the clouds and x is the fraction of cloud cover, then the basic formula may be written as

$$A = x \cdot r + (1-x) \cdot A_{min}$$

from which we have the fraction of cloud cover, x , as:

$$x = \frac{A - A_{min}}{r - A_{min}} \quad (2)$$

This formula requires a knowledge of r which varies.

A way to estimate the cloud reflectance r , is by observing the difference between the Earth's surface temperature and the temperature equivalent of the satellite-observed daytime infrared reading (denoted by IR_D). The radiance of the IR_D by Stefan's law is equal

to $5.75 \times 10^{-8} T^4$ (watts/m²), where T is the temperature equivalent in degrees Kelvin. Putting $z = (\text{surface temperature} - T)$, (units degree Kelvin), the following relationship has been observed:

$$r = -0.000265z^2 + 0.0295z + 0.10. \quad (3)$$

A surface temperature of 30° C for latitudes within 25 degrees of the equator and -5° C for latitudes within 25 degrees of the pole was used. Interpolations were used for intermediate latitudes.

Using this method, the proportion of cloud cover was calculated for each day of the year over the 4-year period covering the entire globe. We considered the data for the four seasons separately, and we developed a separate cloud cover model for Winter, Spring, Summer, and Fall, where Winter consists of the months December, January, and February, etc.

Because this investigation is based on derived cloud cover estimates and may be subject to criticism, it is noted that ground-based cloud observations are also estimates as well as cloud cover obtained by satellite photography. We make this conjecture: Those variables which are not well defined in the IR to cloud cover conversion procedure will have small contributions to climatic modeling of the clouds over the entire season. For a specific day and area the preceding procedure may not be entirely satisfactory for synoptic cloud cover analysis. It should be noted that because of the orbit of the TIROS satellite the estimates in the near polar regions are degraded somewhat.

A PROBABALISTIC MODEL FOR CLOUD COVER

The proportion of cloud cover over any grid square is a random variable which has some probability distribution associated with it. Falls [3] found that the Beta distribution could be used to represent

the probability distribution of the proportion of cloud cover.

Henderson-Sellers [5] has also found the Beta distribution useful as a model for the probability distribution of the proportion of cloud cover. The Beta probability density function with parameters a and b is given by:

$$f(x) = \frac{\Gamma(a+b)}{\Gamma(a)\Gamma(b)} x^{a-1} (1-x)^{b-1}$$

for $0 \leq x \leq 1$, $a > 0$, $b > 0$

The Beta probability density function can assume a variety of shapes. It can be mound shaped, U-shaped, or J-shaped with varying amounts of skewness. Table 1 shows the relationship between the a and b parameters and the shape of the frequency curve.

TABLE 1: Shapes of the Beta Probability Density Function
For Different a and b Parameters

Shape	Parameters	
Mound	$a > 1$	$b > 1$
J	$a > 1$	$b < 1$
Reverse J	$a < 1$	$b > 1$
U	$a < 1$	$b < 1$
Uniform (0,1)	$a = 1$	$b = 1$

The question arises as to how well the Beta distribution actually fits the cloud cover data at hand. To answer this question we first estimated the a and b parameters using the method of moments. These estimates are given by

$$\hat{b} = (1 - \bar{x}) [\bar{x} (1 - \bar{x}) - s^2] / s^2$$

$$\hat{a} = \bar{x} \hat{b} / (1 - \bar{x})$$

where \bar{x} is the sample mean proportion of cloud cover, and s^2 is the sample variance of the proportion of cloud cover. Next, we constructed histograms for the cloud cover at several grid locations. A grid location was selected at random from latitude circles 12.5°

apart beginning with 50° N latitude and extending to 62.5° S latitude. A histogram was constructed for each selected location on the basis of the cloud cover data for the Winter quarter (December, January, February) for the four years of data. Each of the histograms were constructed on the basis of approximately 350 cloud cover values. The corresponding Beta curves are shown superimposed on the histograms in Figures 1 - 2.

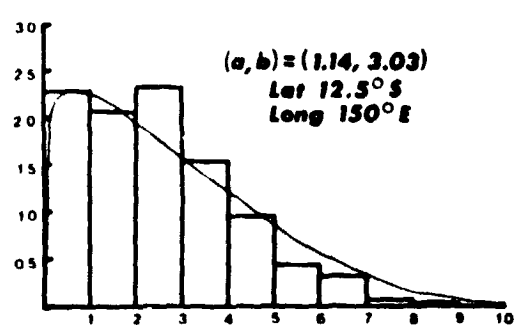
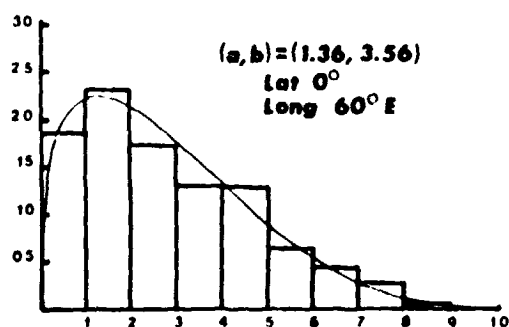
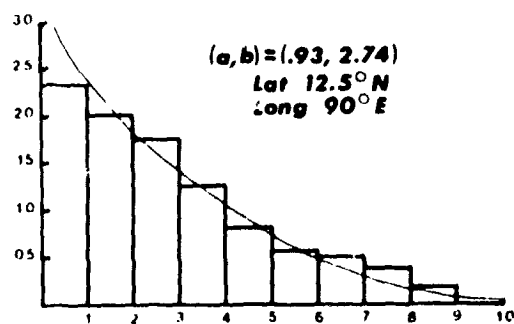
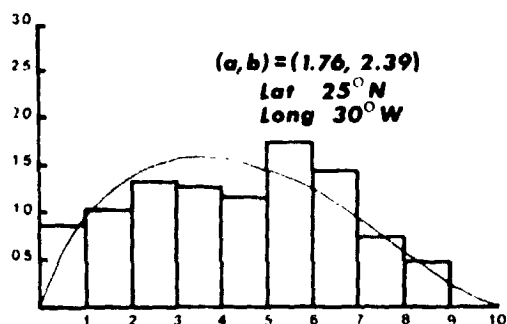
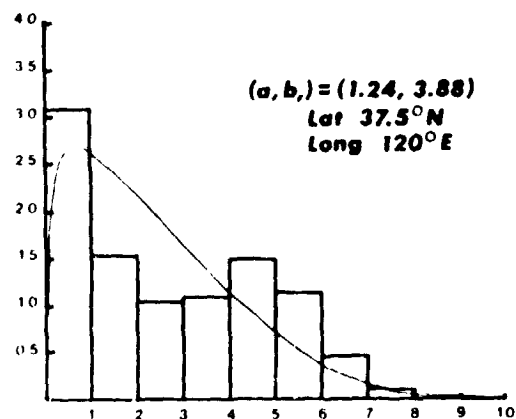
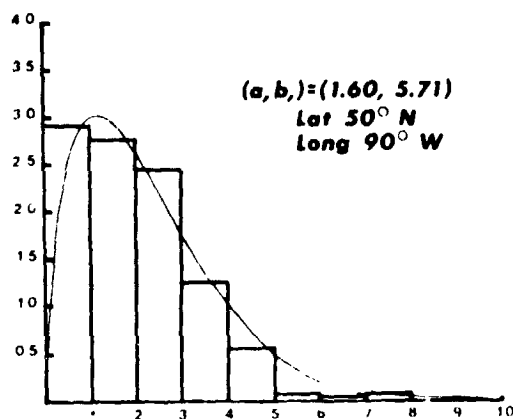


Figure 1: Histograms of the Proportion of Cloud Cover with Beta Curves Superimposed

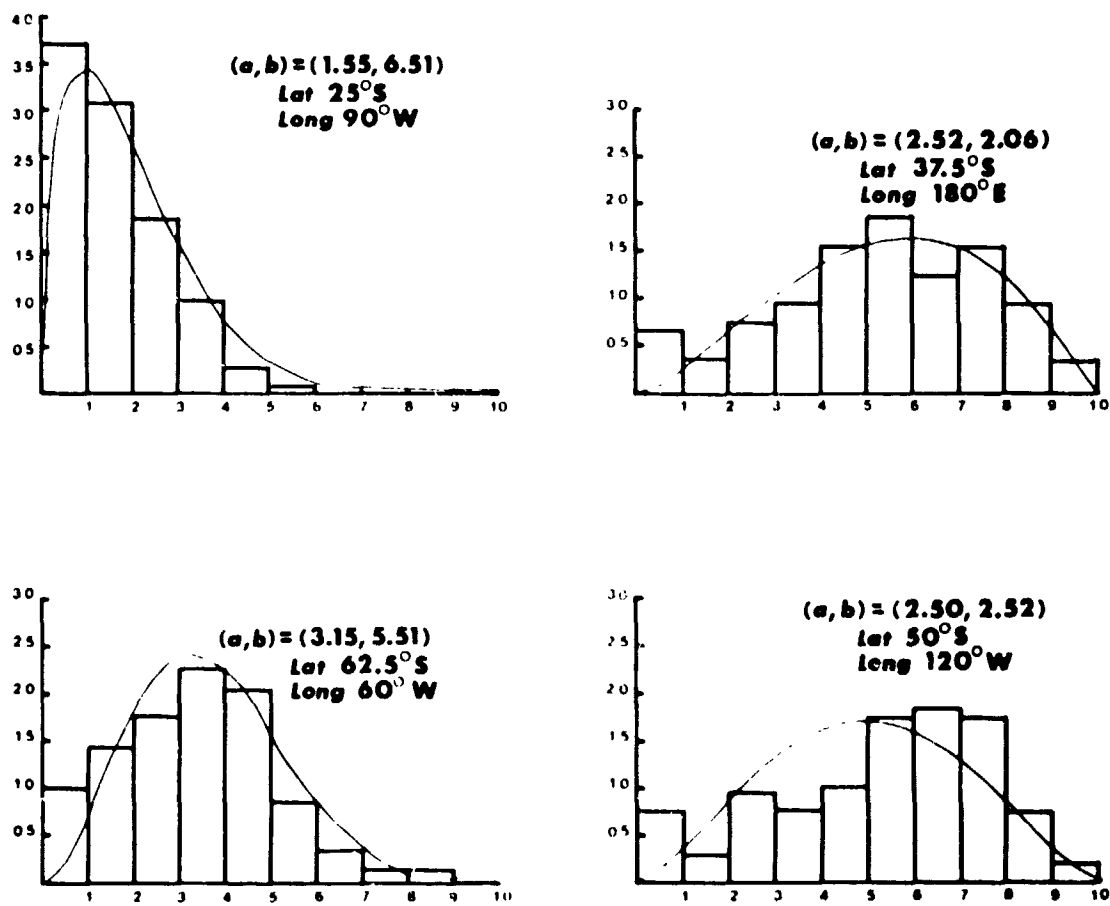


Figure 2: Histograms of the Proportion of Cloud Cover with Beta Curves Superimposed

A WORLD WIDE CLOUD COVER MODEL USING THE BETA DISTRIBUTION

The (a,b) parameters of the Beta distribution give a good deal of information about the cloud cover characteristics of a given location as illustrated in the previous table and figures. Thus, we used the estimated parameters (\hat{a}, \hat{b}) in determining regions of homogeneous cloud cover.

As a first step, it is instructive to consider the frequency histograms of the calculated (\hat{a}, \hat{b}) values for each of the four seasons. There are 10,224 grid points over the globe, and each grid point has an (\hat{a}, \hat{b}) pair associated with it for each season. The following frequency histograms (Figures 3-6) of the 10,224 (\hat{a}, \hat{b}) pairs give some indication of where the parameter pairs are falling in the (a,b) plane.

	0	250	644	386	141	122
5.0	4	171	391	257	165	114
4.0	3	346	710	662	327	149
3.0	18	487	727	1150	598	148
2.0	10	209	242	378	249	104
1.0	16	140	226	148	32	30
0						
	.5	1.0	1.5	2.0	2.5	
	a					

Figure 3: Winter Frequency Histogram for Global (\hat{a}, \hat{b}) Values

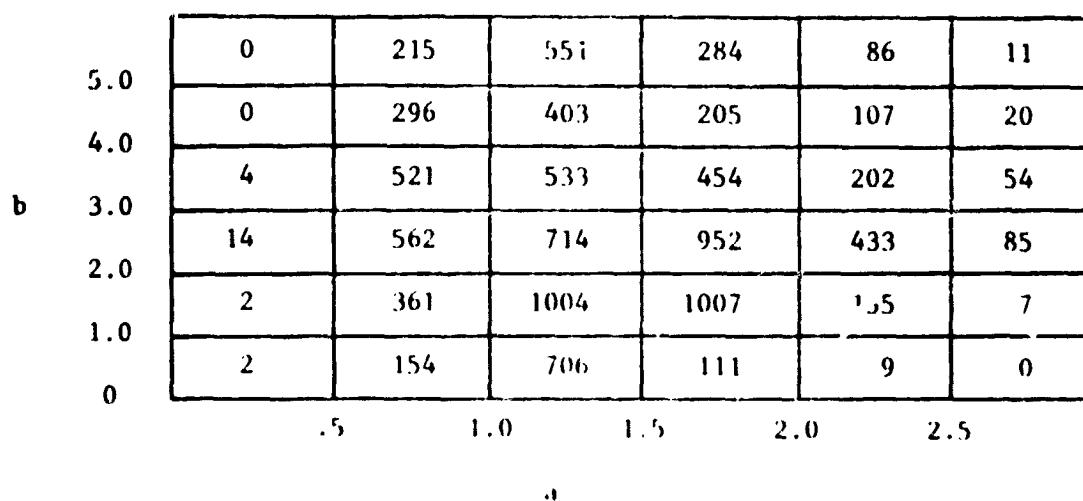


Figure 4: Spring Frequency Histogram for Global (\hat{a}, \hat{b}) Values

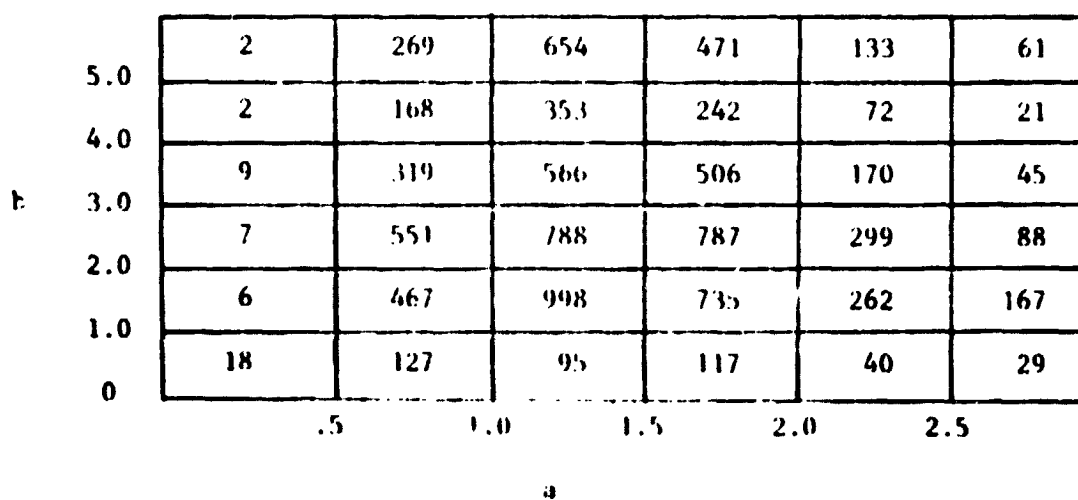


Figure 5: Summer Frequency Histogram for Global (\hat{a}, \hat{b}) Values

b	5.0	1	163	406	244	96	27
	4.0	0	224	312	106	32	21
	3.0	7	44	549	387	250	82
	2.0	42	765	752	1104	509	86
	1.0	27	304	677	937	316	91
	0	0	102	456	482	152	22
			.5	1.0	1.5	2.0	2.5
			a				

Figure 6: Fall Frequency Histogram for Global (\hat{a}, \hat{b}) Values

The numbers in the above frequency histograms indicate how many (\hat{a}, \hat{b}) parameters over the entire globe fall in the specified block.

For example, there are 644 (\hat{a}, \hat{b}) pairs globally such that $1.0 < \hat{a} \leq 1.5$ and $\hat{b} > 5.0$ in the Winter quarter.

The 36 regions in the (\hat{a}, \hat{b}) plane from the frequency histogram for global (\hat{a}, \hat{b}) values form a basis for determining homogeneous cloud cover regions. Grid points on the globe which have (\hat{a}, \hat{b}) parameters falling in the same block have very similar cloud cover characteristics. This concept leads to a preliminary cloud cover model. Each grid point on the globe is assigned to one of 36 groups depending on the block in which (\hat{a}, \hat{b}) falls. A FORTRAN program was used to label each grid point with 0 - 9 or A - Z depending on the group the grid point fell into. These labels were printed in a rectangular array maintaining the latitude and longitude position of each point. This procedure results in a map of the globe containing a large number of contiguous regions which have the same basic cloud cover characteristics. The resulting maps are shown in Figures 7-10

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Figure 7: Global Cloud Cover Classification Based on
(a,b) Parameters of the Beta Distribution
- Summer

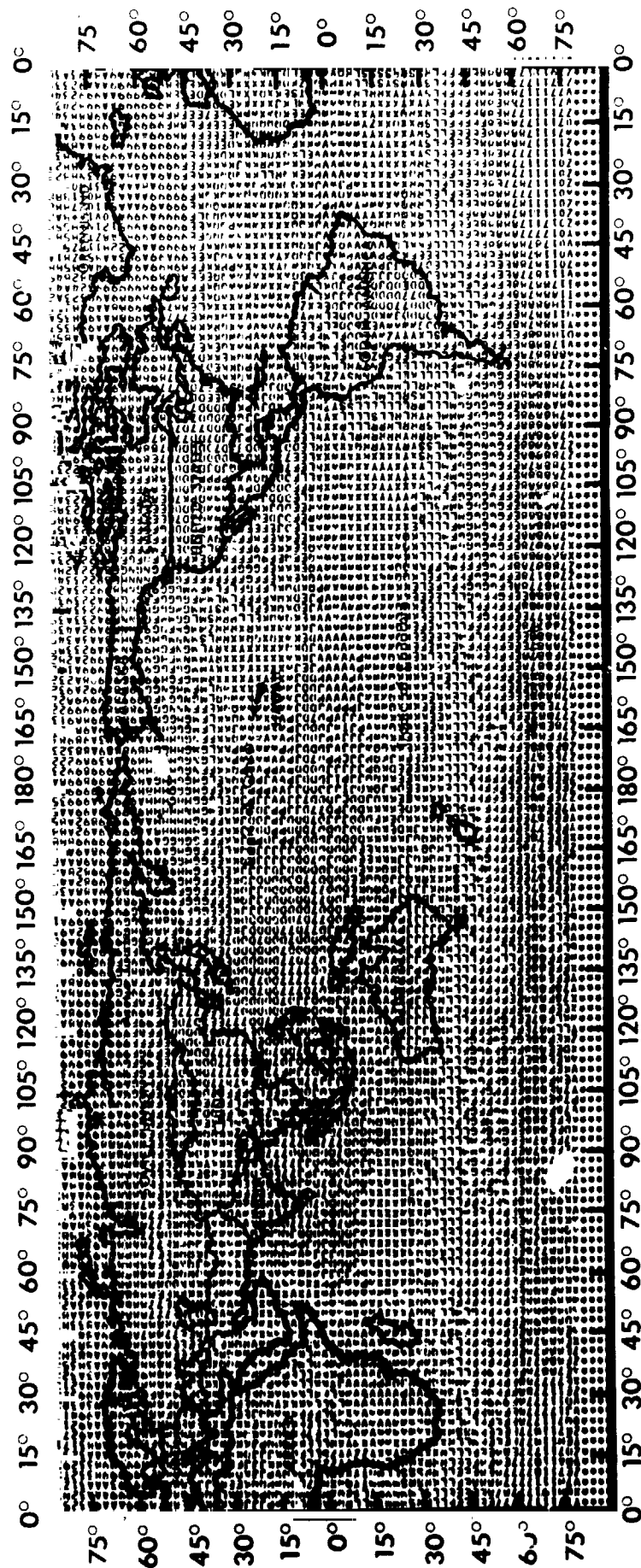


Figure 8: Global Cloud Cover Classification
Based on (a,b) Parameters of the Beta
Distribution - Fall

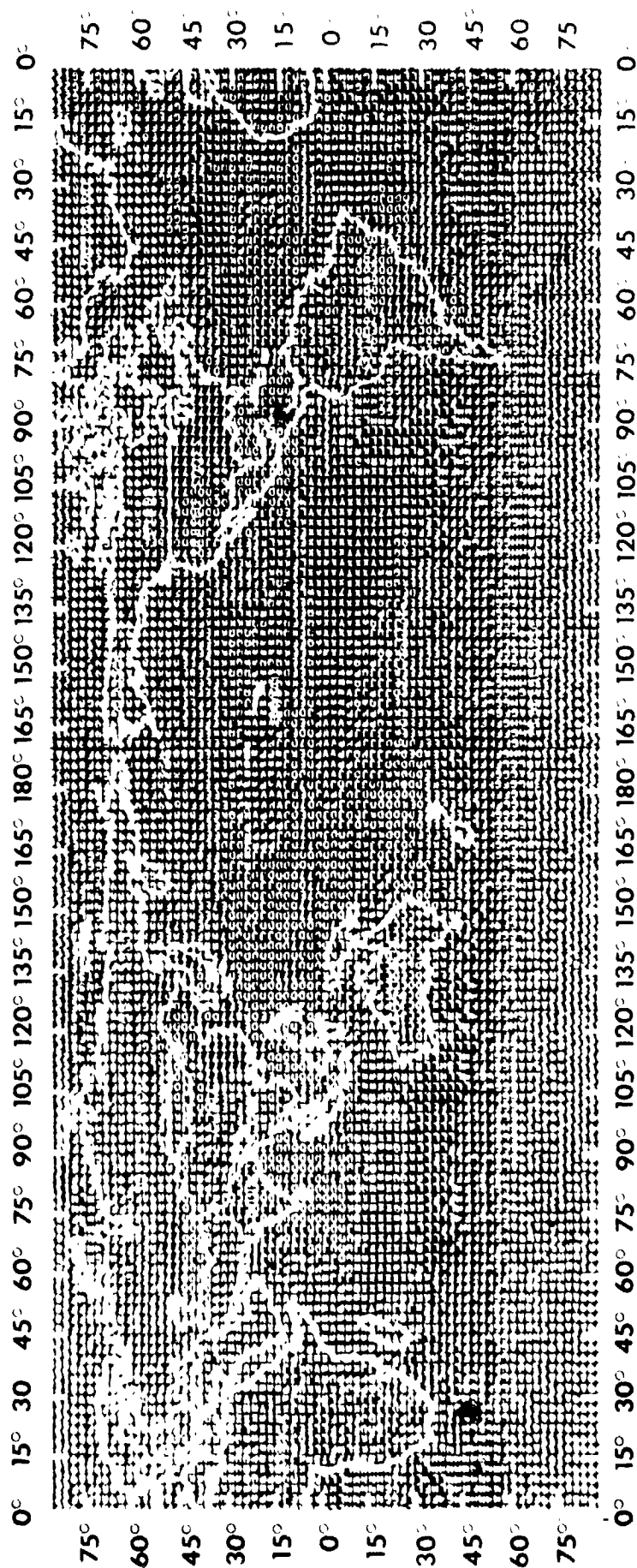


Figure 9: Global Cloud Cover Classification Based
on (a,b) Parameters of the Beta Distribution
- Winter

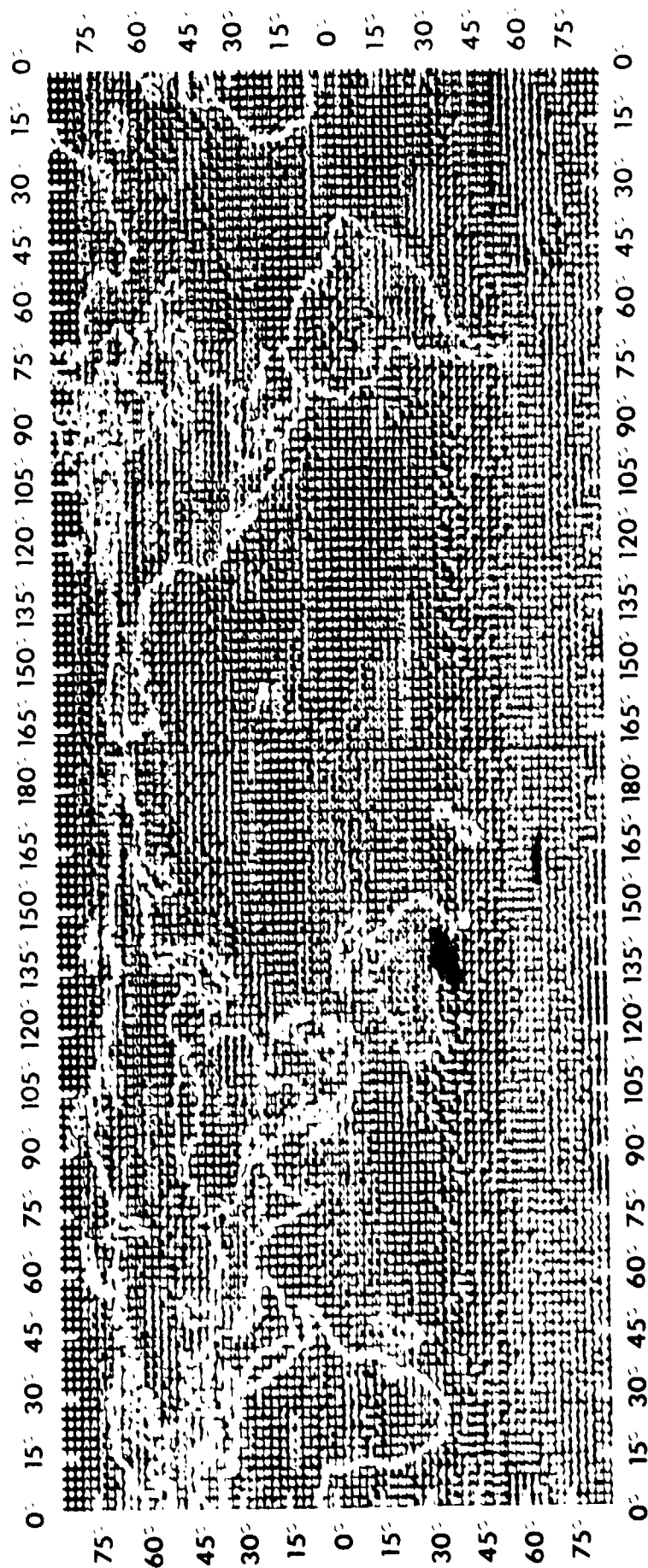
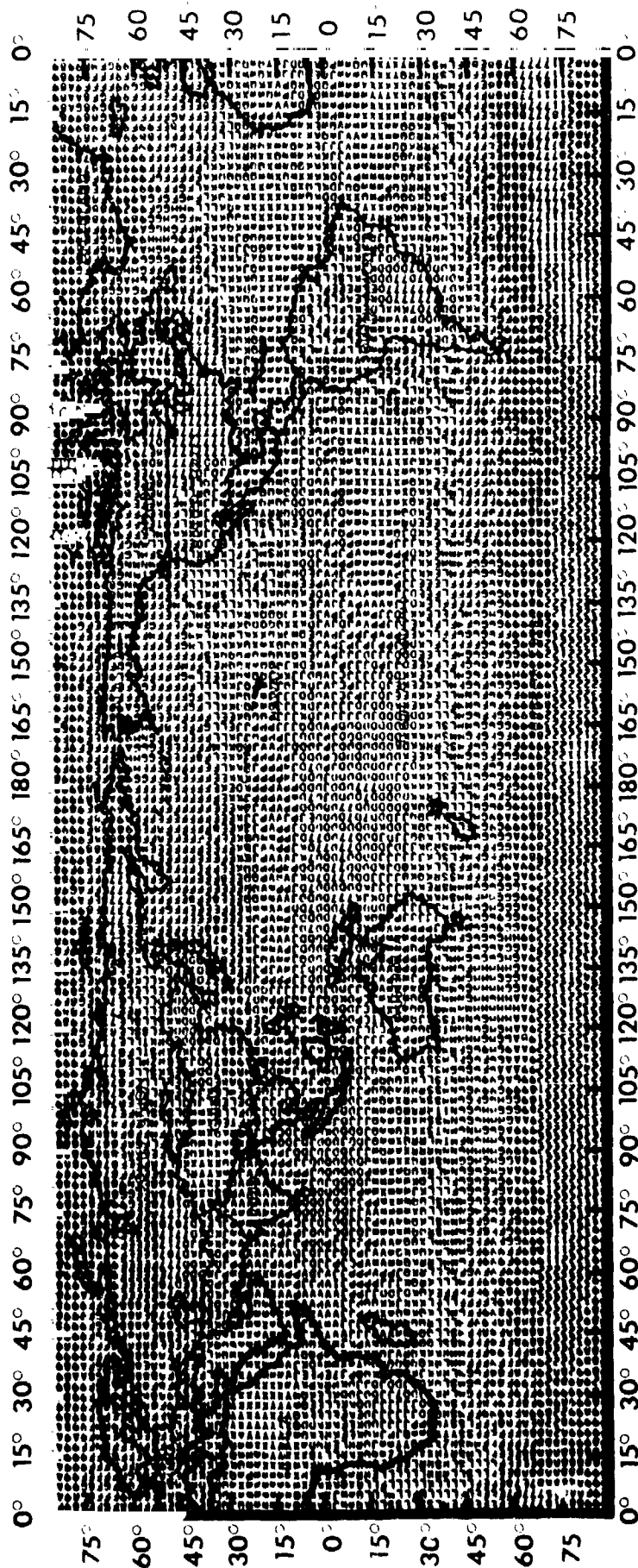


Figure 10: Global Cloud Cover Classification Based on
(a,b) Parameters of the Beta Distribution
- Spring



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with global maps superimposed. These maps have been simplified by combining several of the 36 blocks and recoding the maps. The recoded maps are shown in Figures 15-18. The key for the original and maps is given in Figure 11. The key for the recoded maps is given in Figure 12.

	U	V	W	X	Y	Z
5	O	P	Q	R	S	T
4	I	J	K	L	M	N
3	C	D	E	F	G	H
2	6	7	8	9	A	B
1	0	1	2	3	4	5
0						

.5 1.0 1.5 2.0 2.5

a

Figure 11: Code for Original Homogeneous Cloud Cover Regions Map

The maps may be interpreted according to the distributional characteristics of the various regions. Typical Beta frequency curves for the 9 recoded regions are given in Figures 13-14.

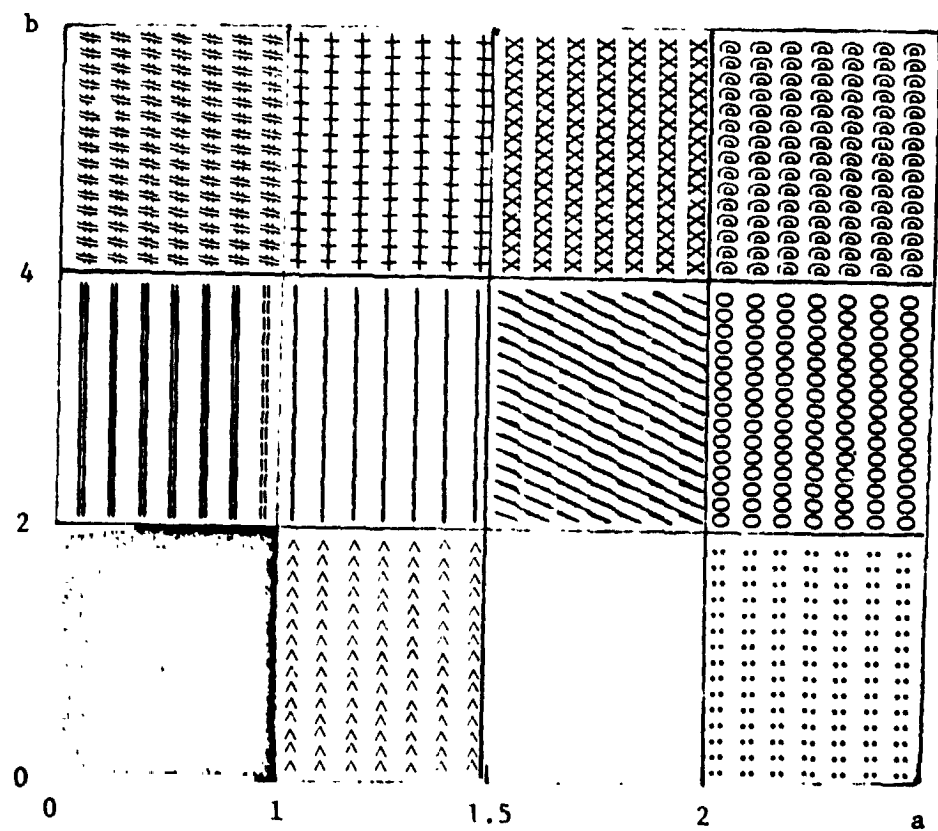


Figure 12: Key For Recoded Homogeneous Cloud Cover Regions Map

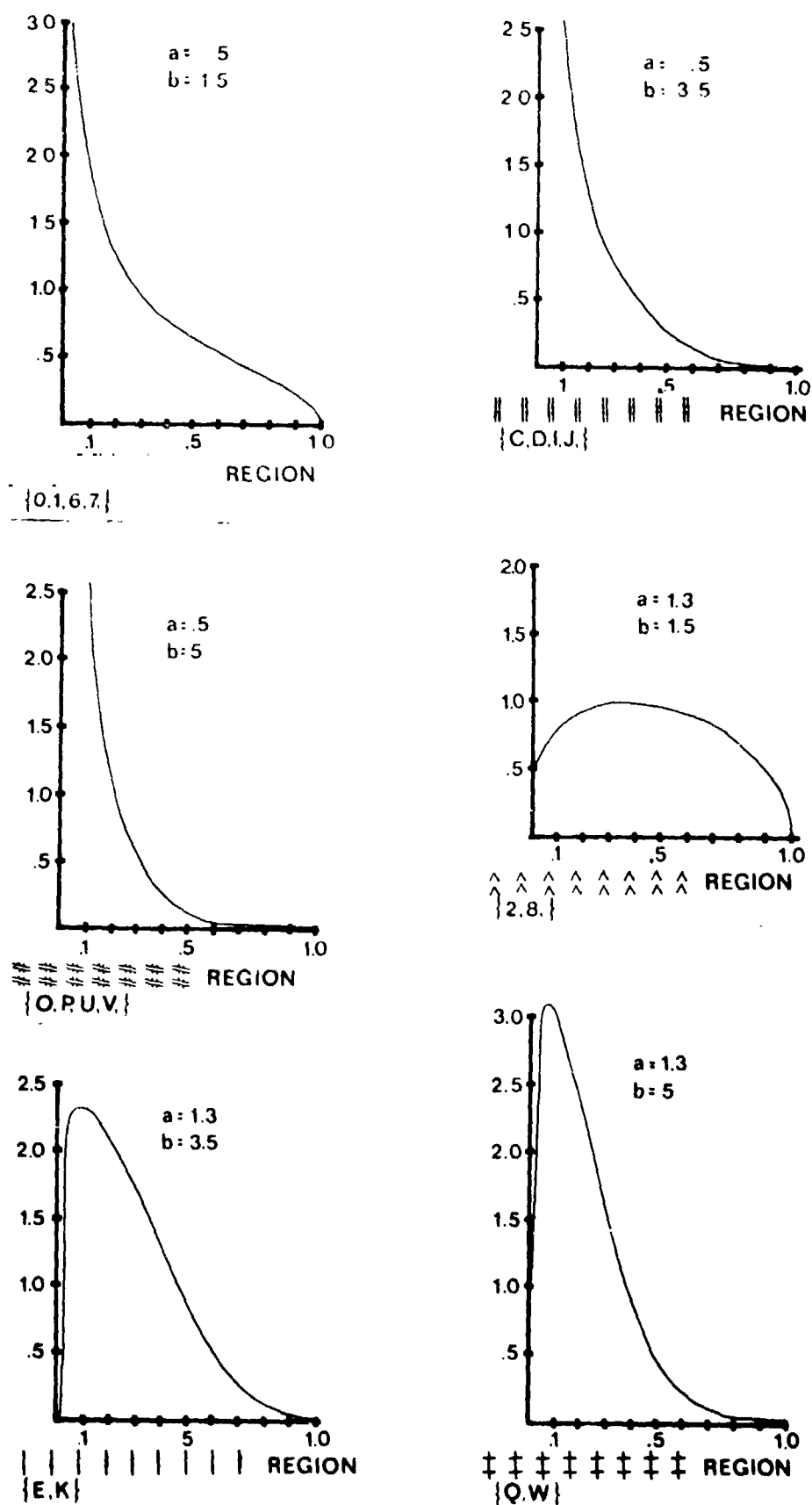


Figure 13: Typical Beta Curves for Specified Regions in the (a,b) Plane

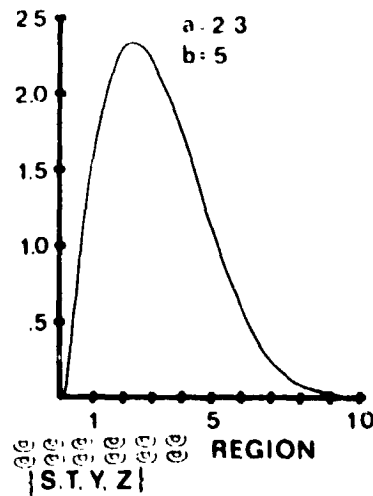
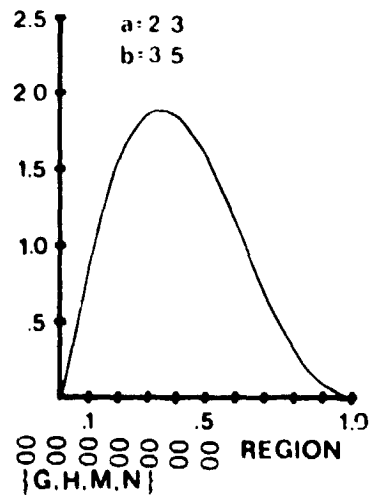
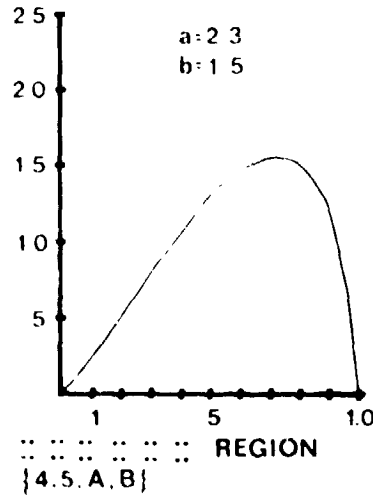
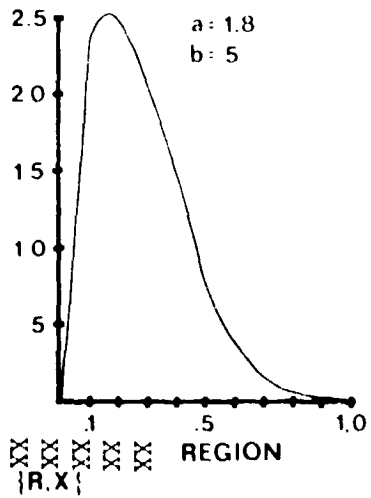
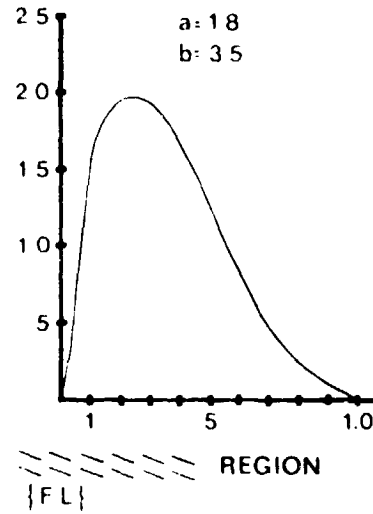
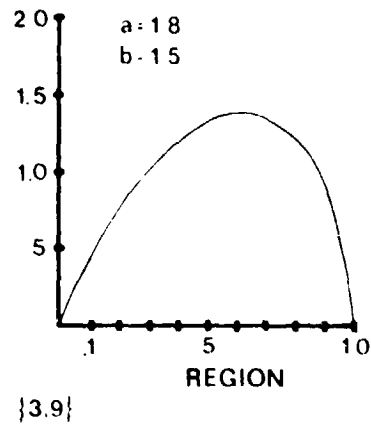


Figure 14: Typical Beta Curves for Specified Regions in the (a,b) Plane

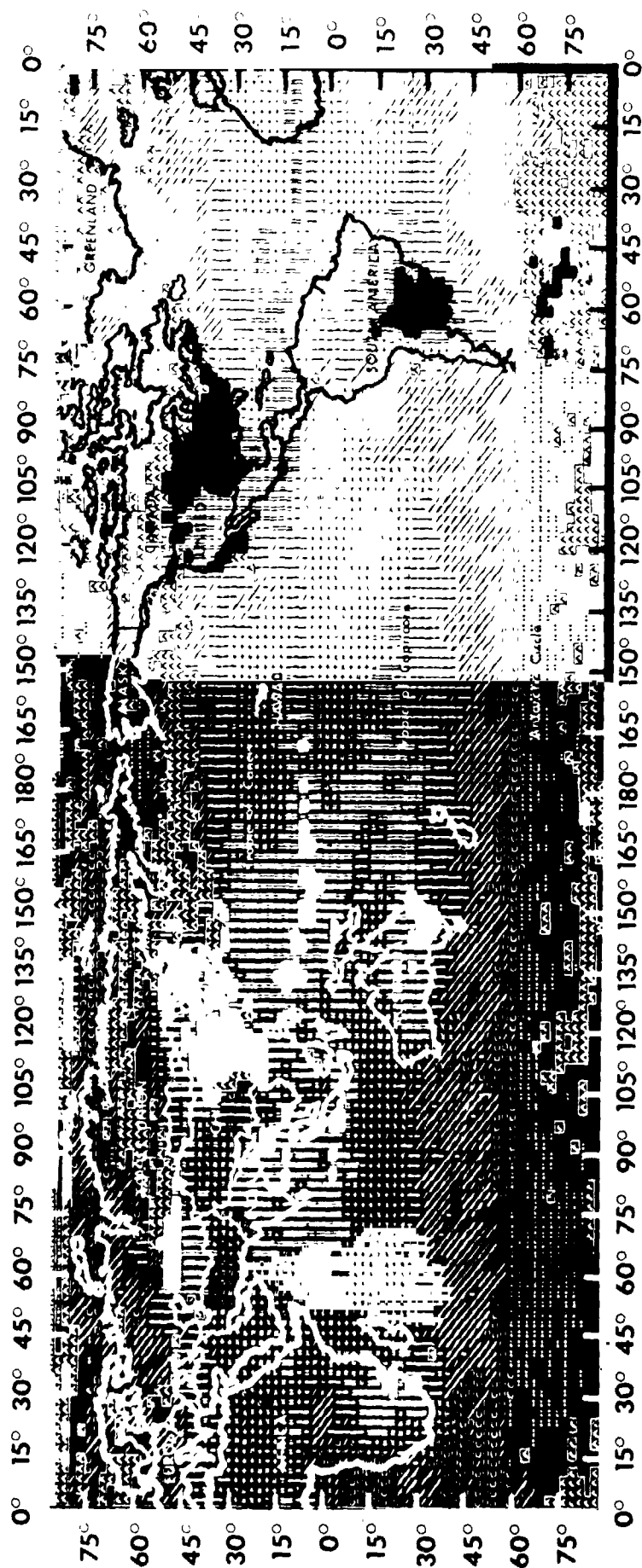


Figure 16: Global Cloud Cover Classification Based on
(a,b) Parameters of the Beta Distribution
- Fall

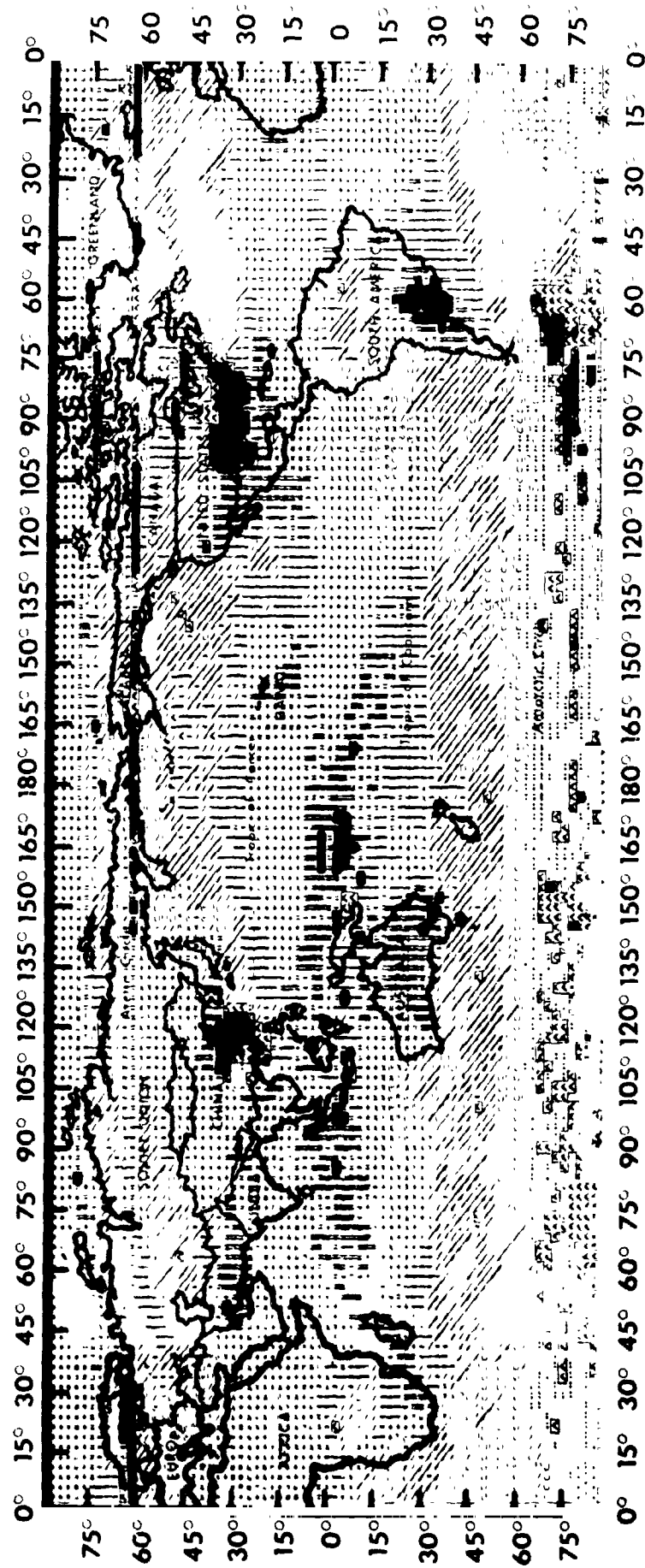


Figure 17: Global Cloud Cover Classification Based on
(a,b) Parameters of the Beta Distribution
- Werner



Figure 18: Global Cloud Cover Classification Based on
 (a,b) Parameters of the Beta Distribution
 - Spring

WORLD WIDE CLOUD COVER MODEL USING MEAN AND STANDARD DEVIATION CONTOUR LINES

One may wish to determine mean and standard deviation of the proportion of cloud cover at any given location. To do this we have developed contour maps which give the mean or standard deviation. The methodology is similar to that used to determine homogeneous cloud cover regions. We first calculated the mean and standard deviation of cloud cover for each grid point for a particular season. To obtain a contour map for the mean cloud cover for a particular season we used a FORTRAN program to print the first digit of the mean cloud cover for each grid point on the globe maintaining the latitude and longitude position. Contour lines were then traced on a transparent map overlaying the printout. Separate maps were constructed in the same way for the standard deviation of cloud cover. These maps are shown in Figures 19-26.

The maps in Figures 19-26 may be used as a general guide to the cloud cover characteristics for any place on the globe. Also, the mean and standard deviation of the proportion of cloud cover obtained from these maps may be used (in the absence of the previously given maps in Figures 7-10) to obtain estimates for the parameters (a,b) in the Beta distribution.

CONCLUSIONS AND RECOMMENDATIONS

The current cloud cover model illustrates a useful objective methodology for cloud cover classification. The developed maps can be useful for those who need some information regarding the cloud cover characteristics for any particular location on the globe. This is particularly useful in that the practicing climatologist can

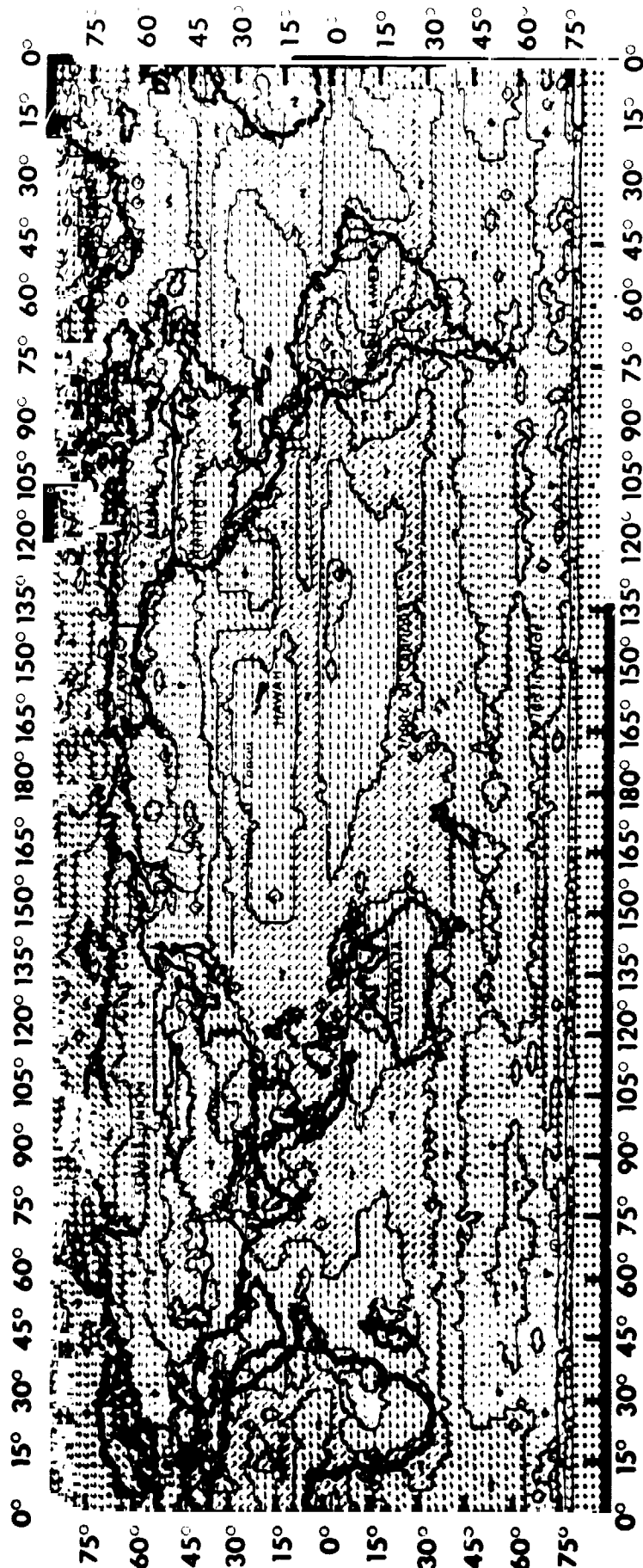


Figure 19: Mean Cloud Cover - Summer Digit Printed x 10 =
Mean Percent Cloud Cover

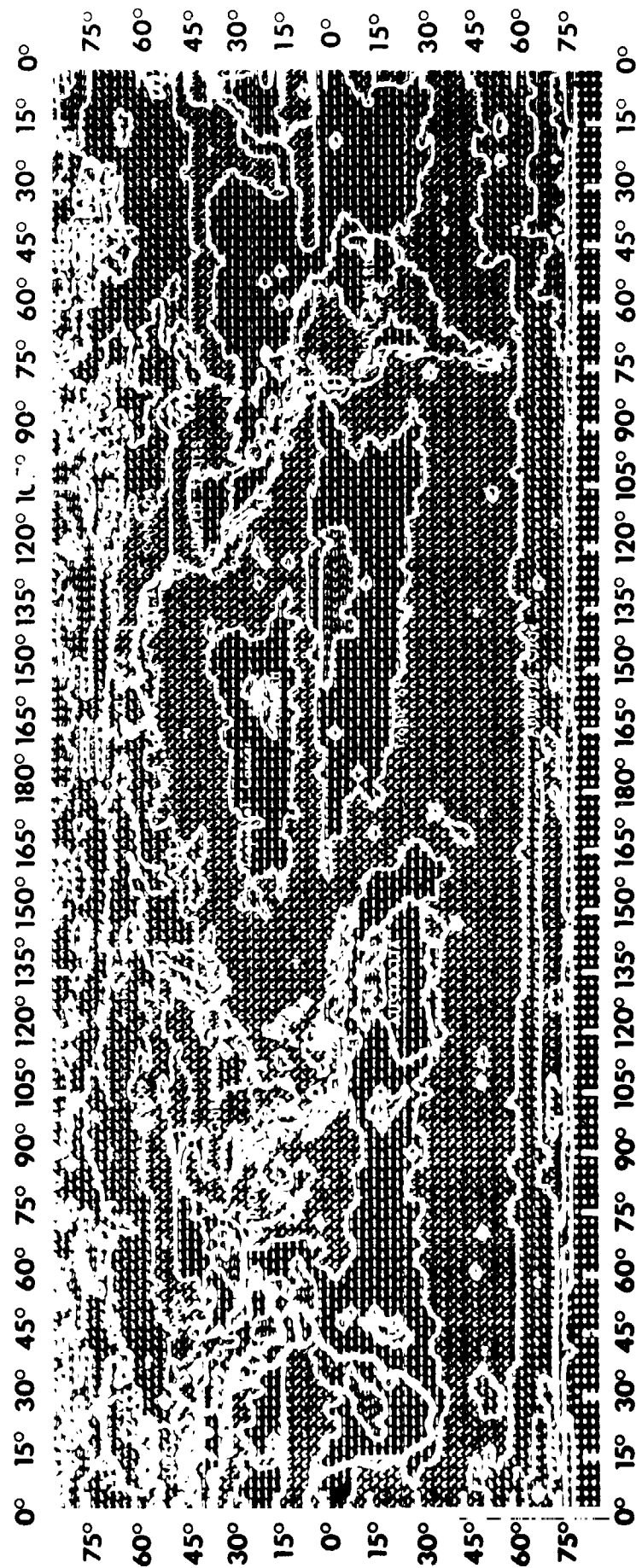


Figure 20: Standard Deviation Cloud Cover - Summer
Digit Printed x 10 = Standard Deviation

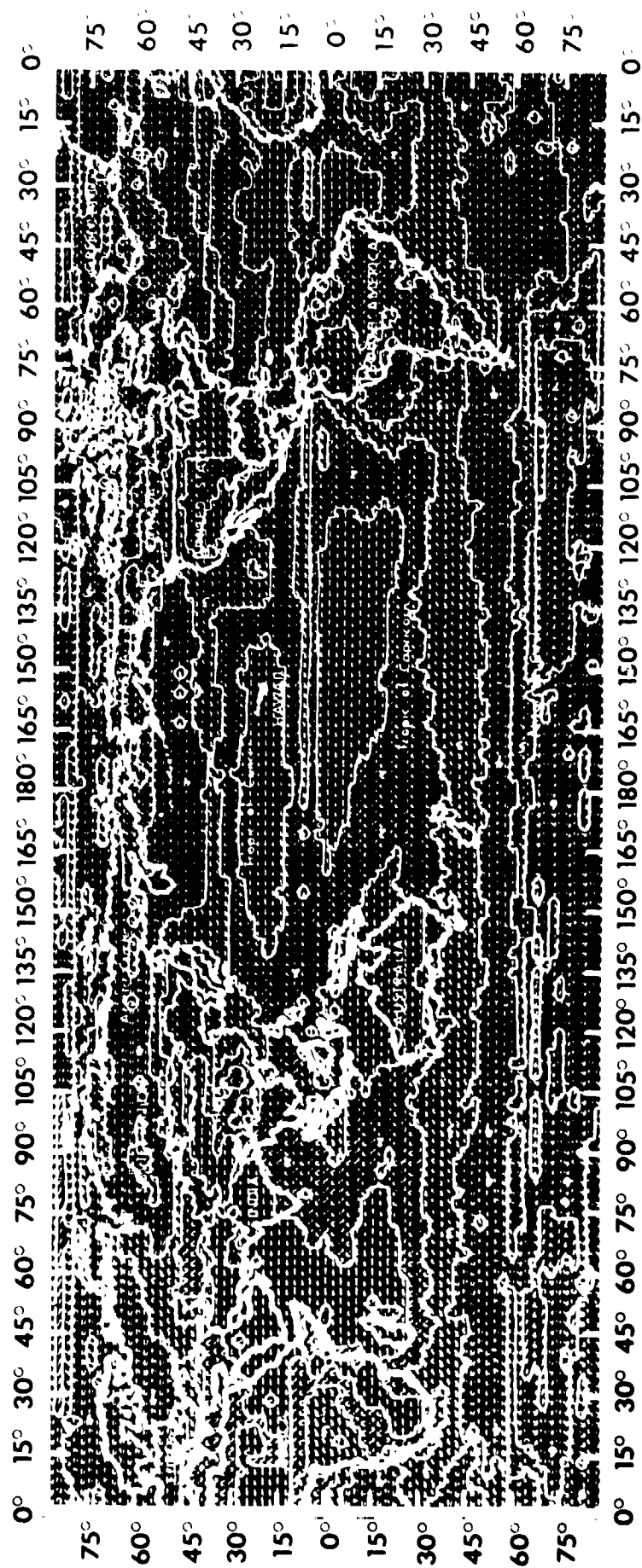


Figure 21: Mean Cloud Cover - Fall

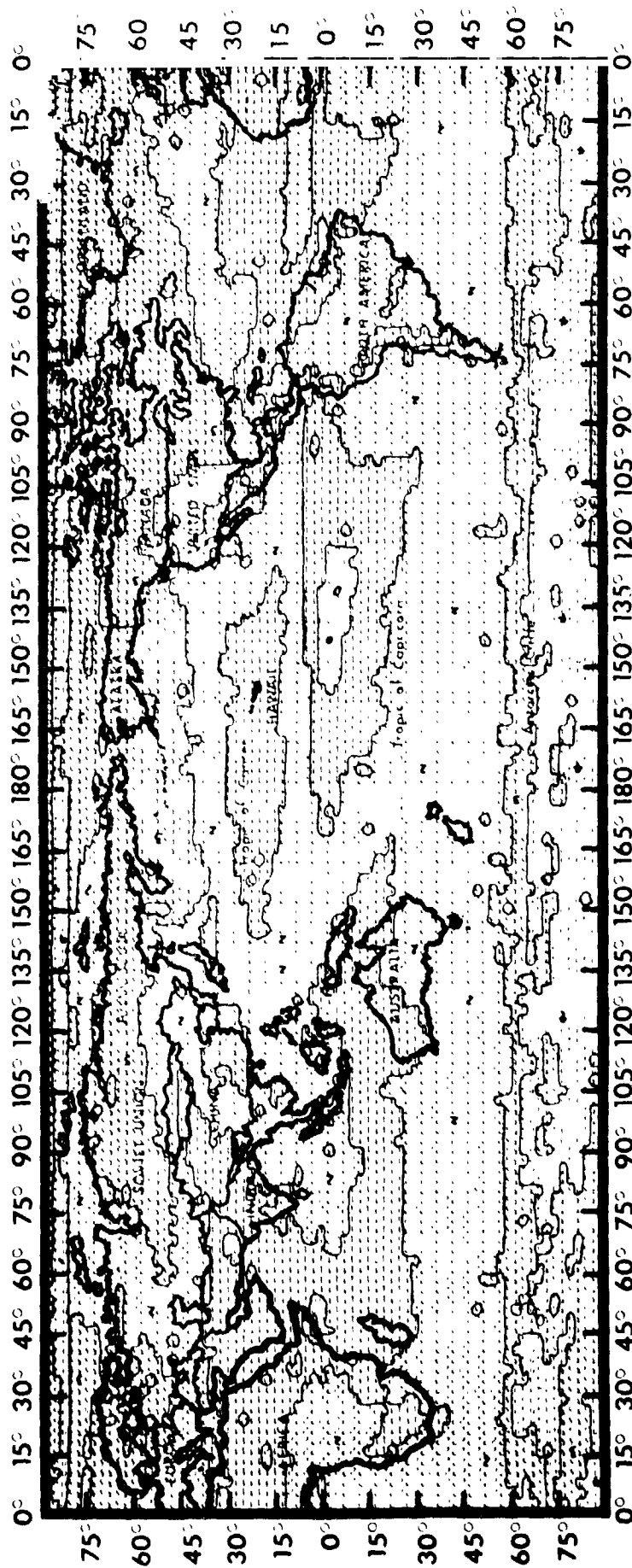


Figure 22: Standard Deviation of Cloud
Cover - Fall

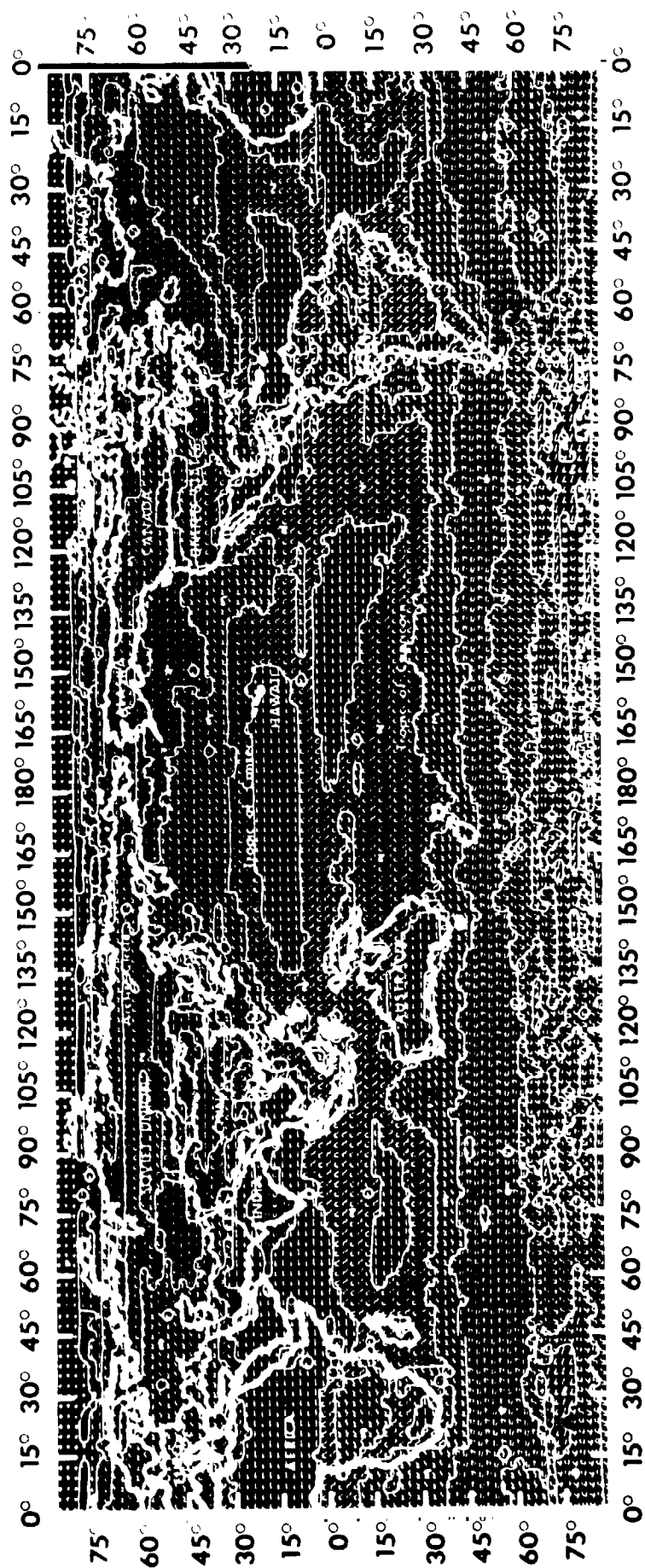


Figure 23: Mean Cloud Cover - Winter

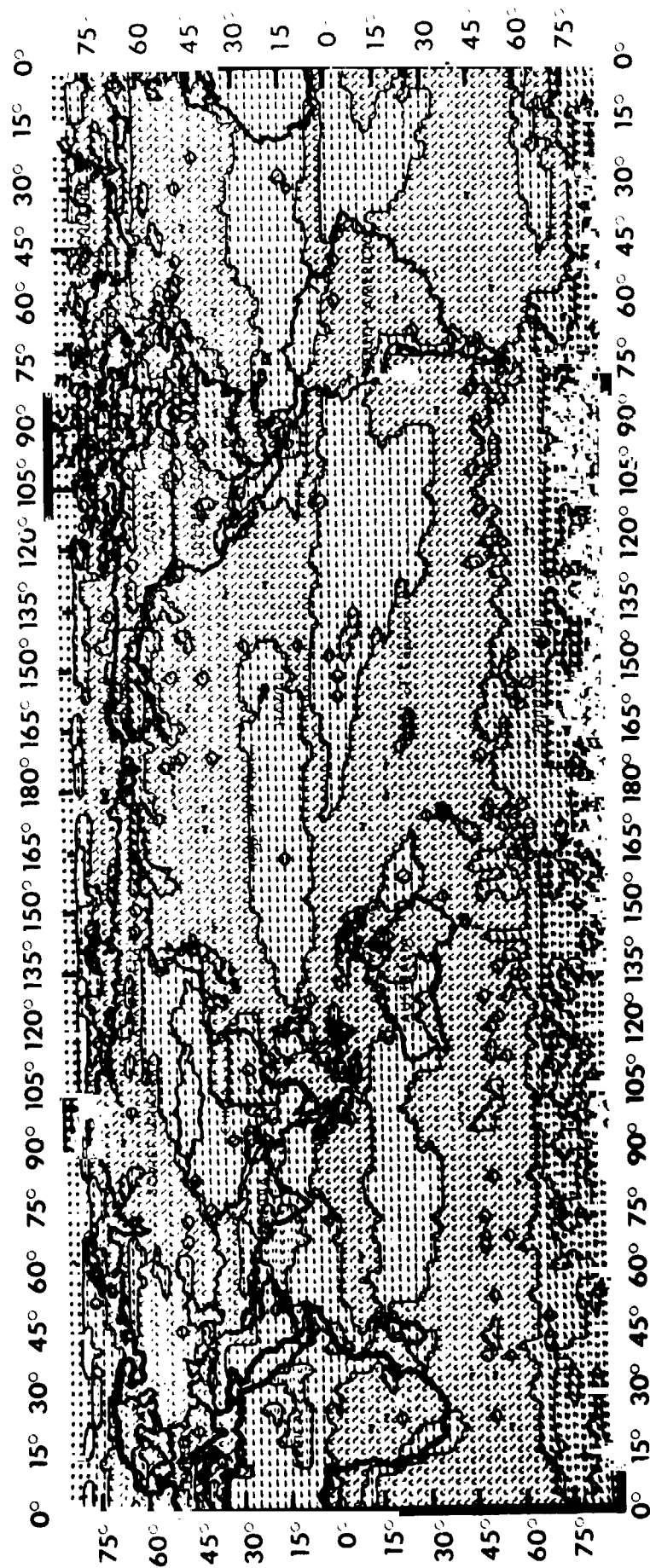


Figure 24: Standard Deviation of Cloud Cover
 .. Winter

Figure 25: Mean Cloud Cover - Spring

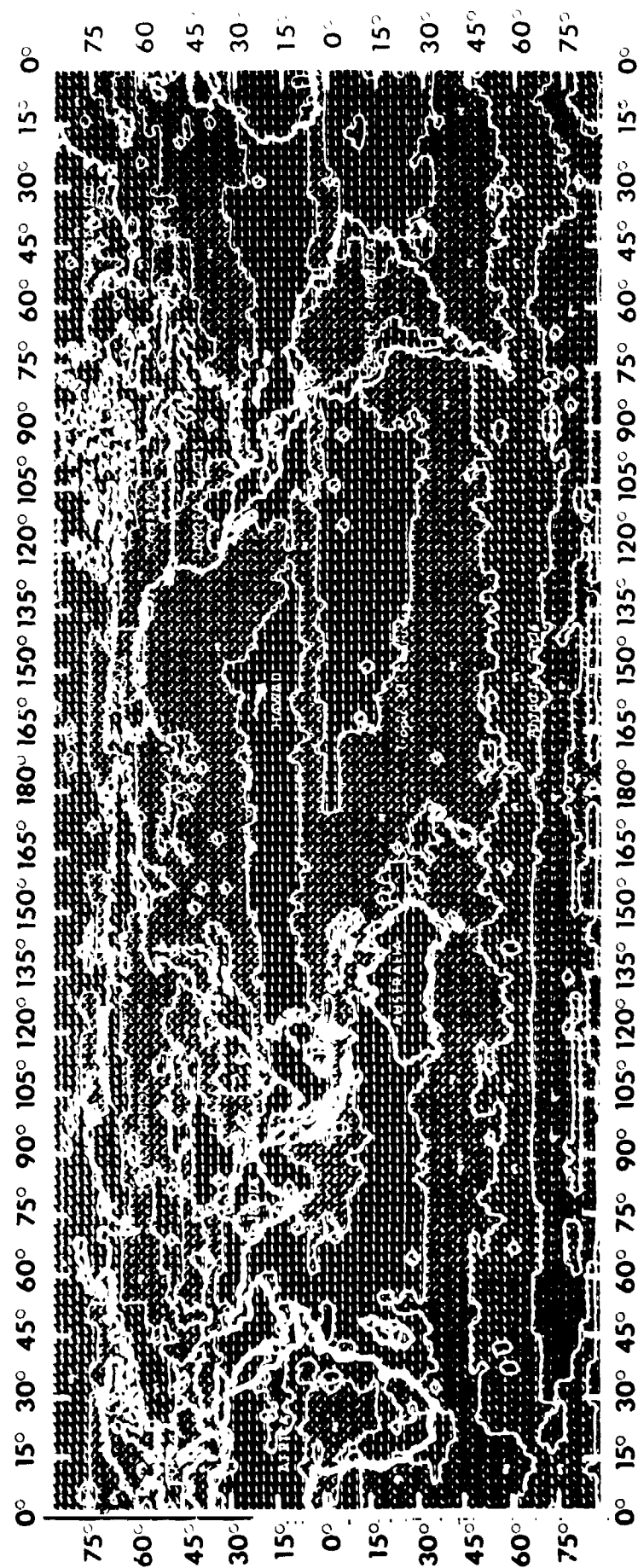


Figure 26: Standard Deviation of Cloud Cover
- Spring

obtain a great deal of cloud cover information without going through large volumes of data.

There are problems with the current cloud cover model. The most obvious of these is the lack of data. To make a good climatological model a reasonably long record length is required. The satellite data available for this study comprise approximately 44 months. This is sufficient for some model development, but a longer period of record would be desirable. Also, temporal persistence cuts down on the actual number of independent cloud cover observations. Another problem is that the cloud cover used in the model is derived. This is not to say that the cloud cover values used are not accurate, but the derived cloud cover should be compared with some independently observed cloud cover. It should be noted that any type of cloud cover measurement will have some degree of error associated with it.

The topic of error analysis in the estimation of the parameters (a,b) was not covered for several reasons. There are several types of errors which made the problem quite complex. First, as previously mentioned, there is an unknown error component in the derived cloud cover itself which may vary from place to place. Also, there is error in recorded satellite measurements. The cloud cover values have a temporal correlation which is not fully known. The short length of the record certainly contributes to the error (the degree of error depends on the temporal persistence of cloud cover and the long term cyclic behavior of cloud cover). Another factor is that the satellite measurements were taken for a given grid location at the same time each day.

It is worth remarking that even with the above-mentioned errors, it is still possible to use the data at hand to classify areas of the globe into homogeneous cloud cover regions. The methodology is sound, and the presently developed models should give a good overall picture of global cloud cover characteristics.

The above comments lead to three major recommendations. First, the derived cloud cover should be verified using some independent measurements. Second, spatial and temporal persistence of cloud cover need to be investigated. Third, the model should be updated with a longer length record.

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